www.czasopisma.pan.pl PAN POLSKA AKADEMIA NAUK www.journals.pan.pl

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2021.139947
2022, No. 52 (I–III): 81–86

An integrated approach for landslide hazard assessment: A case study of the Middle Dnieper Basin, Ukraine

Olena Ivanik[1)] ✉, Joana Fonseca[2)], Oleksandr Shabatura[1)], Ruslan Khomenko[1)], Kateryna Hadiatska[1)], Dmytro Kravchenko[1)]

[1)] Taras Shevchenko National University of Kyiv, Institute of Geology, 60, Volodymyrska str., Kyiv, 03001, Ukraine

[2)] City, University of London, School of Mathematics, Computer Science and Engineering, Department of Civil Engineering, London, United Kingdom

RECEIVED 07.11.2020 REVIEWED 12.04.2021 ACCEPTED 24.05.2021

Abstract: Ukraine is characterised by active natural hazards processes within different structural, tectonic and landscape zones. In Middle Dnieper basin region mass movement processes have great impact on people's livelihoods and infrastructure. These processes occur on the slopes with different geological structure. The determining causes include lithologic and stratigraphic conditions, hydrogeological regime, structural and textural peculiarities of rocks and the geomorphology of the slopes. Landslide inventory database has been developed based on long-term observations of more than 400 landslides and landslide-prone areas. This paper takes efforts forward by combining different geological and geophysical methods to advance the current understanding of landslide phenomena and contributing towards a better informed assessment of landslide hazard and risk. The developed methodology is implemented in a test sites of Kyiv region, covering an area of 18.3 km^2 situated in the Middle Dnieper basin. Electrical Resistivity Tomography, Self-Potential and Infrared Thermography techniques were employed to investigate the lithostratigraphic sequences, the geometry of landslide body and potential mass movement. The results presented here confirm the potential of using an integrated approach that combines different field data to better plan mitigation activities and measures for the effective land management. This study will be useful in increasing the safety aspects of the infrastructures and lives and also for planning of research and developmental activities.

Keywords: Dnieper River basin, Electrical Resistivity Tomography (ERT), Infrared Thermography (IRT), landslide hazards

INTRODUCTION

The predicting of the impact of geological hazards on the infrastructure for prevention of emergency situations and mitigation of associated economic and human risks is the topical issues for the natural hazards risks assessment. The solution to this problem involves two aspects. First aspect includes targeted territorial research aimed at the recognition of the formation mechanisms of geological hazards under numerous natural and man-caused factors. Second aspect envisages the development of the state-of-the art and effective tools providing analytical and information support of the targeted research and measures for the prevention of hazards and their qualitative and quantitative assessment. Recognised global practices of the investigation of geological hazards underline the efficiency of GIS tools and modelling approaches for the predicting, prevention and mitigation of negative impact caused by mudflows, landslides, flooding and other natural hazards. Appropriate methods and tools have been developed by, e.g., Geological Surveys of USA, Great Britain and other countries [Foster *et al.* 2008; Garcia-Rodriguez *et al.* 2008]. The landslide hazards are assessed from the statistical analysis, remote sensing data and field surveys. Laser scanning of the topography is one of advanced techniques used for landslide monitoring to create high precision and high resolution DEM models either on raster grids or via TIN networks [Jaboyedoff *et al.* 2012]. Geophysical methods also play an important role for the analysis and monitoring of geohazards.

Landslides are the major natural hazard in the Ukraine. Increasing resilience against landslide hazard is a priority for the Ukrainian government and local communities due to the high impact on infrastructures. Over 23,100 landslides are recorded in the country.

It is important for the people to be informed of landslide hazards that may affect their wellbeing. A better understanding of the causes and spatial distribution of landslides will help guide environmental protection policies in the Ukraine.

Mass movement processes occur on the slopes with specific structure and specific composition of rocks. The main causes of these movements are the lithology of deposits, the hydrogeological regime, structural and textural features of rocks and degree of slopes. The triggering factors include precipitation, dynamic processes that change the stability of slopes, weathering, tectonic movements, seismicity and human impact. Each of the processes of mass movement requires special approaches to their study and prediction [Ivanik *et al.* 2019].

In Kyiv region the mass movement processes have significant impact on the infrastructure. Therefore it is of great importance to predict these geohazards and assess potential risks.

An inventory map of landslides within Kyiv region has been developed. It is based on long-term observations of more than 400 landslides and landslide-prone areas.

These landslide investigations were conducted to document the occurrence of landslide phenomena in Kyiv region and investigate the types, distribution, morphology and dynamics of landslides in relation to morphological and geological characteristics. The information on landslides in the landslide inventory map is applied for the identification the areas where landslides are present and have been recognised and for susceptibility models of landslide hazards.

The database of landslides contains parameters of these objects including depth of surface of rupture, lithology, dimensions, etc., and a description of their causes and impact on the infrastructure. This database has been applied for the susceptibility mapping of landslides in Kyiv region. A landslide susceptibility map shows the areas that have the potential for mass movement. These areas are determined by correlating some of the principal factors that contribute to landsliding (geomorphology, tectonic units, lithology, thickness of deposits and others) with the past distribution of landslides. It is necessary to note that these maps indicate only the relative stability of slopes; they do not make absolute predictions.

Absolute predictions of landslide hazards at the large scale requires an integrated approach that combines remote sensing data, geological and geophysical methods. This study allows to make definitive conclusions about specific geological and geodynamic conditions necessary to ensure most efficient methods and technics of landslide hazards prediction. Moreover, the use of integrated approach surely suppresses uncertainties, number of which is quite high when only a single method is used.

STUDY MATREIALS AND METHODS

STUDY METHODS

Assessment and predicting of landslide hazards includes the monitoring and modeling of landslide processes for the large scale predicting of landslide hazards with implication of remote sensing (use of Unmanned Aerial Vehicles – UAV and satellite imagery), geophysical methods (electrical resistivity tomography – ERT), geomagnetic surveying, self-potential method (SP) and infrared tomography (IRT) (first time usage in Ukraine). The research entails the application of multiple non-invasive geophysical techniques in order to control and monitor landslide hazards in Kyiv region. The ERT is applied to landslides in order to investigate both the lithostratigraphic sequences and the geometry of landslide body (lateral extension and thickness) [Marescot *et al.* 2008; Reynolds 1997; Telford *et al.* 1990]. The ERT technique is based on the measurement of the electrical resistivity values and their spatial distribution in the subsoil. This method has been applied to landslides in order to define the presence of new cracks that could indicate an early stage formation of a new landslide [Perrone *et al.* 2014]. Resistivity changes depend on the alteration water saturation conditions, as well as differences between geological units. Therefore, during the pre-event phase, ERT is used to gather information both on the geological setting of the potentially unstable area and the presence of water tables that could trigger the phenomenon. After-event, the method can help understanding the geometry of the landslide body and estimate the volume of the slide material, with the aim of better planning the mitigation activities [Perrone 2014].

In this study, the processing of ERT data was performed by 2D inversion [Dahlin 1996]. Tomograms with high differentiation of specific electrical resistivity were developed.

SP method is used for imaging water level and water flows within the subsurface at a large scale, as well as their fluctuations over time [Patella 1997; Révil *et al.* 1999; Santoso *et al.* 2019]. Surveys are conducted by measuring natural electrical potential difference between pairs of electrodes connected to a high impedance voltmeter. For landslide observation, the main source of the SP signal is the groundwater flow. The positive SP anomalies correspond to the surface where the water saturation is located, and negative SP anomalies correspond to the zones of infiltration.

IRT proves the presence of potential hazards, such as, zones of discontinuities. In addition, it is used to identify moisture or a seepage zones [Frodella *et al.* 2014]. The IRT method has not been widely applied in landslide investigation. Nevertheless, there is a number of examples that suggest the potential of this method for landslide characterisation [Frodella *et al.* 2014; 2015; 2017; Gigli *et al.* 2014; Wu *et al.* 2015]. According to these earlier studies, thermal anomalies during the landslides investigations can prove the presence of potential hazards, such as, zones of discontinuities, due to the cooling/heating effect of air circulating within open fractures and different thermal transfer capacity of the infilling material related to the exposed sound rock. In addition, it can be used to identify moisture or a seepage zones, due to the surface cooling caused by water evaporation [Frodella *et al.* 2014]. The IRT measurements were carried out here using an Optris® PI640 infrared camera with a 33° lens. By using Optris® PIX Connect software, the obtained surface temperature maps are represented by means of a colour scale.

These methods and special geological field research defines the composition and structure of the most dangerous landslides and areas of soil erosion within two test areas in the Kyiv region. The obtained data is used for large scale prediction of landslide hazards and assessment of slope stability.

CASE STUDIES

Two tested areas were investigated in Middle Dnieper basin. Tectonically, this region is located within the Bila Tserkva (Fastovsky) block on the northern slope of the Ukrainian shield. There are faults of the submeridional, sub-latitudinal, northeast, and north-west direction. The most active are regional structures with a difference in the indicators of total amplitudes of movements up to 60 m. The area belongs to the periglacial subregion. There are deposits of the Paleogene, Neogene and Quaternary geological units. Lithological, stratigraphic, geomorphological and hydrogeological conditions in conjunction with the hydrometeorological factor determine the intensive formation of landslide processes.

Tested areas are different from lithological and geomorphological points of view. The Lake Glynka is located in the city center with a heavy load on the slopes caused by the big concentration of overland and underground utilities, the most important of which is building infrastructure, a network of pipelines, railroads etc. (Fig. 1). All these objects are known by complicated maintenance with periodically due to natural hazards. Here the Paleogene deposits are composed of Eocene-Oligocene sands, the Neogene system is composed by sands of Poltavska series, Quaternary unit is composed by sandy loamy rocks. Glynka is a flooded quarry. The Rzhyshchiv site is located in a rural area, on the coast of Kaniv reservoir and characterised by specific lithological and geomorphological features.

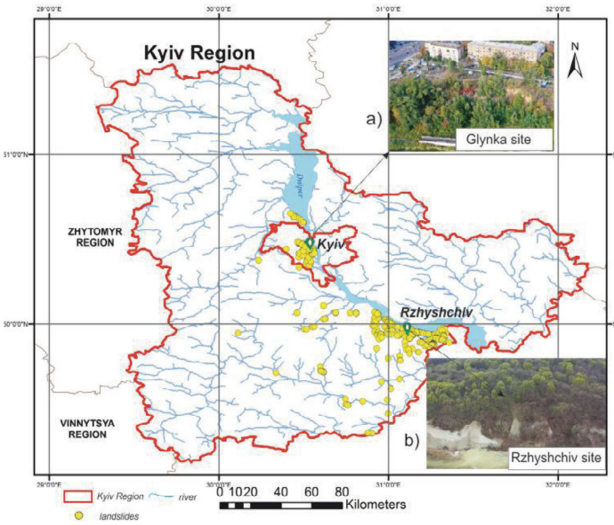

Fig. 1. Distribution of landslides within Middle Dnieper basin, Ukraine: a) Glynka site; b) Rzhyshchiv site; source: own elaboration based on field research and drone images

RESULTS

The main factors contributing to the formation of landslides within this area are the following: i) the steep slope (40-45°), ii) suffosion phenomenon caused by the groundwater outflow to the surface of the slope, and iii) erosion of the low part of the slope due to the changing water level in the lake. There is a real threat of damage of the heating and water supply systems, as landslide processes are constantly spreading towards buildings. The new cracks were observed along the slope flank closer to Mendeleev Street that may suggest the initiation of potential displacement. This aspect was discovered using an integrated approach that integrates the data of Electrical Resistivity Tomography (ERT), self-potential (SP) method and Infrared Thermography (IRT). Figure 2b shows the four electrical resistivity tomograms, with high differentiation of specific electrical resistivity. The location of these four profiles (ERT1, ERT2, ERT3, ERT4) are shown in Figure 2a.

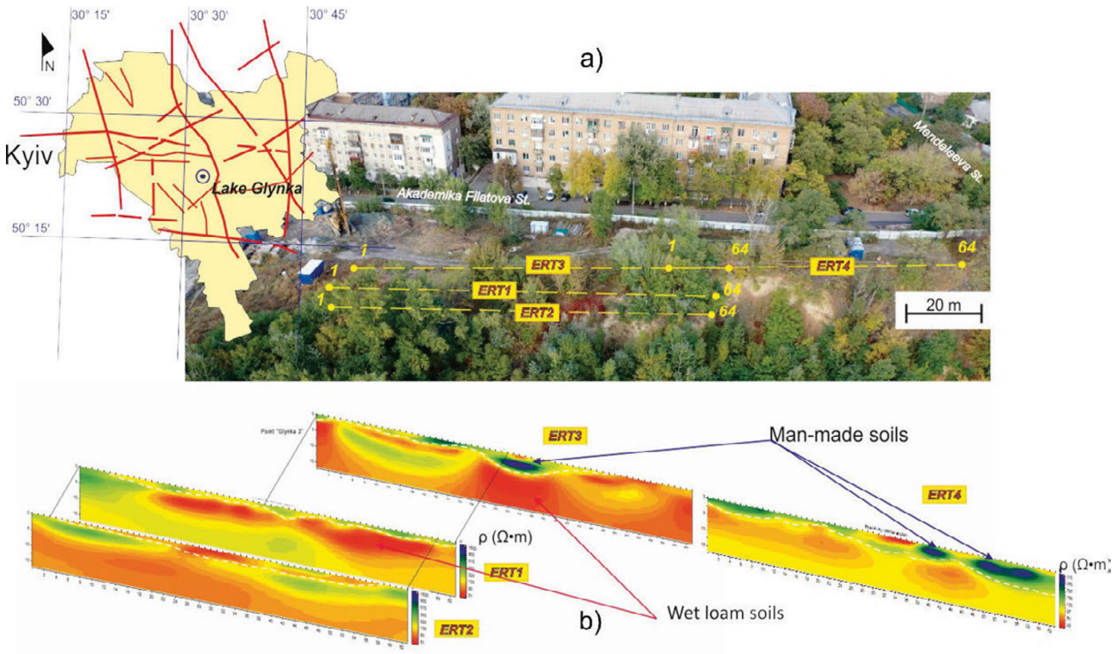

Fig. 2. Data of monitoring the landslide hazards within the Glynka site, Kyiv region: a) aerial photograph of the Glynka site together with its location in Kyiv region, b) profiles of Electrical Resistivity Tomograms (ERT) shown in; the yellow lines in the photograph indicate the ERT profiles; source: own study

The electrical resistivity values range from 6–22 Ω·m (for permeable sediments) to 250–480 Ω·m (for impermeable sediments). Due to the fact that the studied geological section is characterised only by sedimentary rocks, their electrical resistivity is determined mainly by hydrogeological conditions. Deposits in the upper part of the geoelectric section, above the groundwater level, are characterised by maximum values of electrical resistivity, 100 Ω·m. These are soil-vegetation layer, bulk (man-made) soils, deluvial loams, dry loesses and loams. The resistivity of deposits located below the groundwater level is 10–20 Ω·m. Thus, the electrical resistivity in the conditions of the plateau for the saturated loess deposits is on average 70 Ω·m, and in the conditions of landslide slope is 33 Ω·m, for the saturated loams, respectively, 41–42 Ω·m. The new cracks in the ERT field seem as local anomalies with lower resistivity values which situated in the near-surface part of the geoelectric section. The greater the soil moisture in the zones of cracks and penetration of moisture directly into the landslide body, the more clearly these zones are visible on the electrotomogram.

The SP measurements are shown in Figure 3a. There are three local negative SP anomalies on the curve that indicated a reduced value of the measured potential. These suggest the presence of a surface water infiltration zone. The position of these anomalies correlates well with the decreases of electrical resistivity value measured in this zone (Fig. 3c). The observed drop of electrical resistivity value is caused by the increase in water content within the infiltration zone. The positive SP anomaly can be represented as an increase of the measured SP values caused by high water saturation in the landslide body.

The IRT survey was carried out as auxiliary for observations of fracture and weak zones in upper part of the profile. Lower surface temperatures are showed by the dark blue colours, whereas higher surface temperatures are displayed by the lighter yellow colours (Fig. 3b). The low temperature anomalies indicate the moisture zones in the upper part in the profile and correlates with the drop of electrical resistivity value. The hot thermal anomalies indicate the fracture zones look as small crack within 11–14 points and 25–28 points of the profile ERT4 (Fig. 3c). A good correlation between the SP profile and IRT data (Fig. 3b) in particular for the zone between 24 and 32 m, for which the higher temperature measured are believed to be related to water seepage through cracks at the top of the section.

Integrated data of SP, IRT and ERT methods within Rzhyshchiv site determined the lithostratigraphy units, weak zones and places with the high water saturation.

The study area is represented by horizontal layers of Paleogene, Neogene and Quaternary deposits. Geomorphological, lithological, stratigraphic, and hydrogeological conditions in combination with hydrometeorological factors determine the potential development of landslides. The landslides formation in this location is closely related to the groundwater regime of the aquifer in the Oligocene sands, the intensity of saturation of the slope by surface waters and precipitation. The system of landslides in this area is complex and multi-phase. They have combined cascade structure. In the lower part of the slope there are main scarps with the signs of groundwater drainage. The system of landslides was formed as a result of sliding of loess strata along the marls and siltstones, the main and a significant part of subordinate landslides are clearly distinguished. The secondary displacement occurred due to the different amount of water content of each layer of the slope.

The ER tomogram for the Rzhyshchiv site with high differentiation of specific electrical resistivity was created along the profile shown in Figure 4a. The minimum values of electrical resistivity for the saturated loams ranges from 10 to 40 Ω·m and marls are characterised by highest values of electrical resistivity (450–790 Ω·m), as shown in Figure 4b. Most of the processes described above are well visible on the electrical resistivity tomogram.

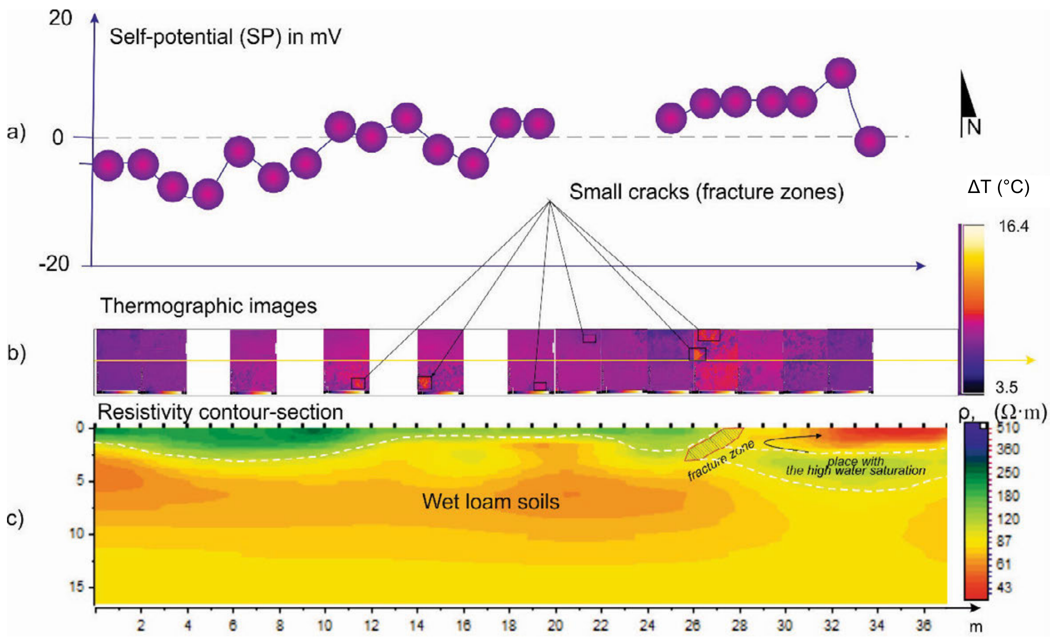

Fig. 3. The integrated data for the landslide hazard assessment within the Glynka site, Kyiv region: a) Self-Potential (SP) data, b) Infrared Thermography (IRT) and c) resistivity data, at Glynka site; source: own study

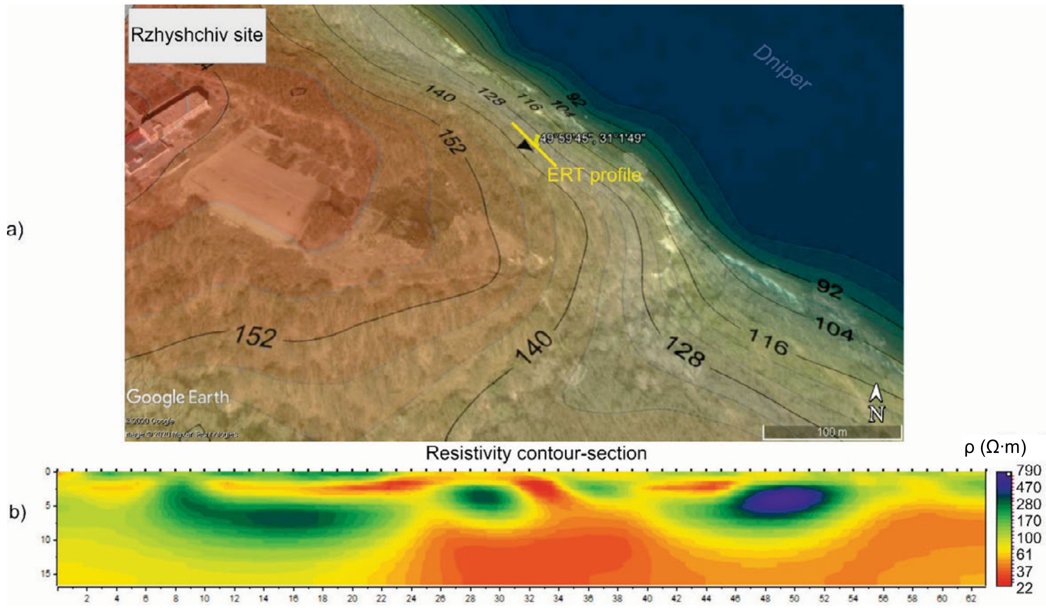

Fig. 4. Electrical Resistivity Tomogram within the Rzhyshchiv site, Kyiv region: a) location of the Electrical Resistivity tomogram shown in b) Electrical Resistivity Tomogram for the Rzhyshchiv site; source: own study

The value of resistivity is influenced not only by the composition of the sedimentary rocks, but also by a large number of factors of different nature: porosity and fracture, humidity, mineralisation of groundwater, rock structure and texture. On the geoelectric section, two peaks (5–7 m) are well observed in the central and right parts of the profiles in the form of two anomalies of reduced values of electrical resistivity (10–27 Ω·m and 37–40 Ω·m). But these anomalies differ in nature: in the central part the values of electrical resistivity increase from the periphery to the center, and in the right one vice versa. It refers the different lithological composition and degree of the rock moisture. The biggest changes in electrical resistivity associated with the landslide elements are confined to the local low-resistance subvertical zones. These zones correspond to the near-surface parts of the separation cracks. The resistivity of deposits located below the groundwater level is the first tens of Ω·m. As expected, the most changing properties are observed in the coarse sands and cracked rocks.

Having analysed the geological and geophysical information, it is possible to note that low values of specific resistivity, the zones of cracking and new cracks are well distinguished on the geoelectric section. The change of water content and the consequent increase in pore water pressures plays an important role in the triggering mechanisms of these landslides.

DISCUSSION

The presented results confirm the activation of the landslide processes within Lake Glynka, which were detected by magnetic studies of the soil [MENSHOV *et al.* 2020]. As a result, the distribution of magnetic susceptibility within the upper layer of soil and bedrocks was revealed, which, according to the authors, indicates erosion processes as the initial process of landslide activity.

In order to identify the activation of new landslides this area was selected as a tested area for ERT research. It helps to indicate the appearance of new cracks and areas of high water saturation within the slope. Based on the obtained research results, weak zones (presence of cracks) within the landslide slope were detected, which is s on the electrotomograms in the form of local low-resistance subvertical zones. These are signs of erosion processes. Also, the occurrence of gravitational processes in this area is influenced by the structural features of the marl layer, which on the electrotomogram is showed by the form of the highest values of electrical resistance. Signs of activation of landslide processes were also confirmed by monitoring of the mass movement processes [MYKOLAENKO *et al.* 2020] and magnetic studies [VYZHVA *et al.* 2019].

CONCLUSIONS

This study demonstrates the potential of using an integrated approach for landslide characterisation in regions with the complex geological structure. Landslides within Middle Dnieper Basin are triggered by hydrometeorological, geological and morphological factors. They have a complex morphology and structure due to different lithological, stratigraphic, tectonic and hydrogeological conditions. The landslides within this region are structural landslides forming in a quasi-homogeneous environment with a layered structure. Assessment and predicting of landslide hazards includes the monitoring and modeling of landslide processes for the large scale predicting of landslide hazards with implication of remote sensing data, geophysical methods and infrared tomography. These techniques are applied to investigate the lithostratigraphic sequences, the geometry of landslide body and potential mass movement. Combining the data from these methods enables to identify fracture zones and areas with high water saturation, as well as, identify early signs of formation of new displacement. It allows the detection of subsurface structure peculiarities, thus making it possible to confirm the existence of potential sliding zones. A follow up study will use these methods to investigate the probability of spatial occurrence of slope failures in light of the geological conditions and shows areas that have potential for mass movements. The obtained data is used for large scale prediction of landslide hazards and assessment of slope stability. This study will be useful in increasing the safety aspects of the infrastructures and lives and also for planning of developmental activities.

REFERENCES

Dahlin T. 1996. 2D resistivity surveying for environmental and engineering applications. First Break. Vol. 14. Iss. 7 p. 275–284. DOI 10.3997/1365-2397.1996014.

Foster C., Gibson A., Wildman G. 2008. The new national Landslide Database and Landslide hazard assessment of Great Britain [online]. First World Landslide Forum. Tokyo, Japan 18–21 November 2008 p. 203–206. [Access 05.09.2020]. Available at: http://nora.nerc.ac.uk/4694/

Frodella W., Fidolini F., Morelli S., Pazzi V. 2015. Application of Infrared Thermography for landslide mapping: the Rotolon DSGDS case study. Rendiconti Online della Società Geologica Italiana. No. 35 p. 144–147. DOI 10.3301/ROL.2015.85.

Frodella W., Gigli G., Morelli S., Lombardi L., Casagli N. 2017. Landslide mapping and characterization through Infrared Thermography (IRT): Suggestions for a methodological approach from some case studies. Remote Sensing. Vol. *9(12),* 1281. DOI 10.3390/rs9121281.

Frodella W., Morelli S., Gigli G., Casagli N. 2014. Contribution of infrared thermography to the slope instability characterization. [online] Proceedings of World Landslide Forum 3. Beijing, China 2–6 June 2014. [Access 05.09.2020]. Available at: http://hdl.handle.net/11576/2690166

García-Rodríguez M.J., Malpica J.A., Benito B., Diaz M. 2008. Susceptibility assessment of earthquake-triggered landslides in El Salvador using logistic regression. Geomorphology. Vol. 95. Iss. 3 p. 172–191. DOI 10.1016/j.geomorph.2007.06.001.

Gigli G., Frodella W., Garfagnoli F., Morelli S., Mugnai F., Menna F., Casagli N. 2014. 3-D geomechanical rock mass characterization for the evaluation of rockslide susceptibility scenarios. Landslides. Vol. 11 p. 131–140. DOI 10.1007/s10346-013-0424-2.

Ivanik O., Shevchuk V., Kravchenko D., Yanchenko V., Shpyrko S., Gadiatska K. 2019. Geological and geomorphological factors of natural hazards in Ukrainian Carpathians. Journal of Ecological Engineering. Vol. 20. Iss. 4 p. 177–186. DOI 10.12911/22998993/102964.

Jaboyedoff M., Oppikofer T., Abellán A., Derron M.-H., Loye A., Metzger R., Pedrazzini A. 2012. Use of LIDAR in landslide investigations: A review. Natural Hazards. No. 61 p. 5–28. DOI 10.1007/s11069-010-9634-2.

Marescot L., Monnet R., Chapellier D. 2008. Resistivity and induced polarization surveys for slope instability studies in the Swiss Alps. Engineering Geology. Vol. 98(1) p. 18–28. DOI 10.1016/j.enggeo.2008.01.010.

Menshov O., Shevchenko O., Andreeva O. 2020. Integration of magnetic and hydrogeological studies for landslides and soil erosion assessment. Case study from area Lake Glinka (Kyiv, Ukraine). Geoinformatics: Theoretical and Applied Aspects 2020. Conference Proceedings. Vol. 2020. 11–14.05.2020. Kyiv p. 1–5. European Association of Geoscientists & Engineers. DOI 10.3997/2214-4609.2020geo122.

Mykolaenko O.A., Zhyrnov P.V., Tomchenko O.V., Pidlisetska I.O. 2020. Exogenic processes' remote monitoring of Kanivske Reservoir's right bank. Geoinformatics: Theoretical and Applied Aspects 2020. Conference Proceedings. Vol. 2020. 11–14.05.2020. Kyiv p. 1–5. European Association of Geoscientists & Engineers. DOI 10.3997/2214-4609.2020geo099.

Patella D. 1997. Introduction to ground surface self-potential tomography. Geophysical Prospecting. Vol. 45. Iss. 4 p. 653–681. DOI 10.1046/j.1365-2478.1997.430277.x.

Perrone A., Lapenna V., Piscitelli S. 2014. Electrical resistivity tomography technique for landslide investigation: A review. Earth-Science Reviews. Vol. 135 p. 65–82. DOI 10.1016/j.earscirev.2014.04.002.

Reynolds J. M. 2011. An introduction to applied and environmental geophysics. Chichester. John Wiley and Sons Ltd. ISBN 978-0-471-48535-3 (pbk) pp. 710.

Santoso B., Hasanah M.U., Setianto 2019. Landslide investigation using self potential method and electrical resistivity tomography (Pasanggrahan, South Sumedang, Indonesia). IOP Conference Series: Earth and Environmental Science. Vol. 311 p. 1–9. International Symposium on Geophysical Issues. 2–4.06.2018, Bandung, Indonesia. DOI 10.1088/1755-1315/311/1/012068.

Telford W.M., Geldart L.P., Sheriff R.E. 1990. Applied geophysics. Cambridge. Cambridge University Press. ISBN 9780521339384 pp. 792. DOI 10.1017/CBO9781139167932.

Teza G., Marcato G., Castelli E., Galgaro A. 2012. IRTROCK: A Matlab toolbox for contactless recognition of surface and shallow weakness traces of a rock mass by infrared thermography. Computers & Geosciences. Vol. 45 p. 109–118. DOI 10.1016/j.cageo.2011.10.022.

Vyzhva S., Onyshchuk V., Onyshchuk I., Reva M., Shabatura O. 2019. Application of geophysical methods in the study of landslides. 18th International Conference on Geoinformatics – Theoretical and Applied Aspects. Kyiv, May 2019. European Association of Geoscientists & Engineers Source p. 1–5. DOI 10.3997/2214-4609.201902066.

Wu J.H., Lin H.M., Lee D.H., Fang S.C. 2015. Integrity assessment of rock mass behind the shotcreted slope using thermography. Engineering Geology. Vol. 80. No. 1–2 p. 164–173. DOI 10.1016/j.enggeo.2005.04.005.